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Reducing Pulseswidth Broadening in L-Band EDFAs by Use of a New L-Band EDF

Jianjun Yu, Palle Jeppesen, Bera Palsdottir, and Stig N. Knudsen

Abstract—Due to a small effective area of erbium-doped fiber (EDF), a short pulse will be broadened because of self-phase modulation when it is amplified in an L-band EDF amplifier (EDFA); hence, it is necessary to develop a new EDF with large Er^{3+} concentration to reduce the EDF length and a large effective area to reduce the nonlinear effect in the L-band EDFA. In this letter, it will be demonstrated that the pulseswidth can be maintained when a short pulse is amplified in an L-band EDFA consisting of a new L-band EDF.

Index Terms—Erbium-doped fiber, L-band erbium-doped fiber amplifier, self-phase modulation, wavelength conversion.

I. INTRODUCTION

IN ORDER to increase the transmission capacity, terabit wavelength-division multiplexed (WDM) systems using C-band (1530–1565 nm) and L-band (1565–1610 nm) erbium-doped fiber amplifiers (EDFAs) have already been presented [1]. The conventional erbium-doped fiber (EDF) is made with a small effective area and a large difference between the indexes of refraction in the core and cladding [2], [3]. Since the typical length of an EDF is only of the order of several tens of meters in a C-band EDFA, its nonlinear effect is very small. However, the length of an L-band EDFA is several times that of the C-band EDFA [4], [5] and this long length will lead to the fact that nonlinear effects can no longer be ignored. Recently, four-wave mixing (FWM) [2], [3] and XPM [6] in L-band EDFAs have been observed and investigated. Because nonreturn-to-zero (NRZ) signals were used in these references, the peak power was not so large, and consequently self-phase modulation (SPM) in the L-band EDFA was small. However, when a short pulse, for example of a duration of a few picoseconds, is amplified in an L-band EDFA, the pulseswidth will be broadened because of SPM. In this letter, we demonstrate for the first time, pulseswidth broadening in an L-band EDFA consisting of a conventional EDF and we also demonstrate that this broadening pulseswidth can be avoided when the pulse is amplified in an L-band EDFA consisting of a new L-band EDF. This new L-band EDF has a high Er^{3+} concentration and large effective area, which leads to the fact that the length of the EDF, and thereby, the nonlinear effect in L-band can be reduced.

II. EXPERIMENT

A. Gain Characteristics of the L-Band EDFA

In [5], the L-band amplifier consists of a conventional C-band amplifier followed by a length of EDF. An external cavity laser (ECL) provides signal wavelength tunability from 1530 to 1620 nm. The signal power level is adjusted using an attenuator at the input of the C-band/L-band amplifier (OSA). At the output of the EDF, the signal power is measured using an optical spectrum analyzer. The conventional C-band EDFA is based on a counter-propagating 980-nm dual-pumping no-residual pump that could be observed at the output of the EDFA. Two kinds of EDFs are used: conventional EDF and new L-band EDF. The conventional EDF is Al and La codoped with a cutoff wavelength at 953 nm and it is doped with Er^{3+} to a level corresponding to an absorption of 7.4 dB/m at the 1.53- μm absorption peak. The background loss of the EDF measured at 1200 nm is <12 dB/km. The effective area is 17.5 μm^2 . The dispersion at 1550 nm is 2ps/(nm · km). The new L-band EDF is Al and La co-doped with a cutoff wavelength at 924 nm and it is doped with Er^{3+} to a level corresponding to an absorption of 20.4 dB/m at the 1.53 μm absorption peak. The background loss of this new L-band EDF measured at 1200 nm is < 10 dB/km. The effective area is 20 μm^2 . The dispersion at 1550 nm is 1.5 ps/(nm · km). Because the absorption value is increased, the length is chosen to only 50 m, while the length of the conventional EDF is 100 or 130 m. The lengths of the EDFs were not optimized.

Fig. 1(a) shows that the amplified spontaneous emission (ASE) shift toward the L-band region induced by ASE pumping from the EDFA for both the conventional EDF and the new L-band EDF. Fig. 1(b) shows the small signal gain characteristics when the input signal is –25 dBm. Gain of the order of 28 dB is obtained from 1575 to 1600 nm for both the conventional EDF and the new L-band EDF. Fig. 1(a) shows that the length of the new L-band EDF can be reduced because its peak wavelength is shifted to a long wavelength at 1600 nm. A shorter L-band EDF will give flatter gain because the effective length of the L-band fiber is longer than the C-band fiber. For an input signal power of –20 dBm, the ASE noise figure of the L-band EDFAs from 1570–1600 nm is 4–5.5 dB independently of the kind of EDF, but dependent on the signal wavelength.

B. Pulseswidth Broadening in an L-Band EDFA Consisting of a Conventional EDF

Short pulses with 10-GHz repetition frequency, 1568-nm wavelength, 13-dBm average power, and a full-width at half-maximum (FWHM) pulseswidth of 2.3 ps are generated

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J. Yu was with the Research Center COM, Technical University of Denmark, DK-2800 Lyngby, Denmark. He is now with Agere Systems, Murray Hill, NJ 07974 USA.

P. Jeppesen is with the Research Center COM, Technical University of Denmark, DK-2800 Lyngby, Denmark.

B. Palsdottir and S. N. Knudsen are with Lucent Technologies Denmark, DK-2605 Brøndby, Denmark.

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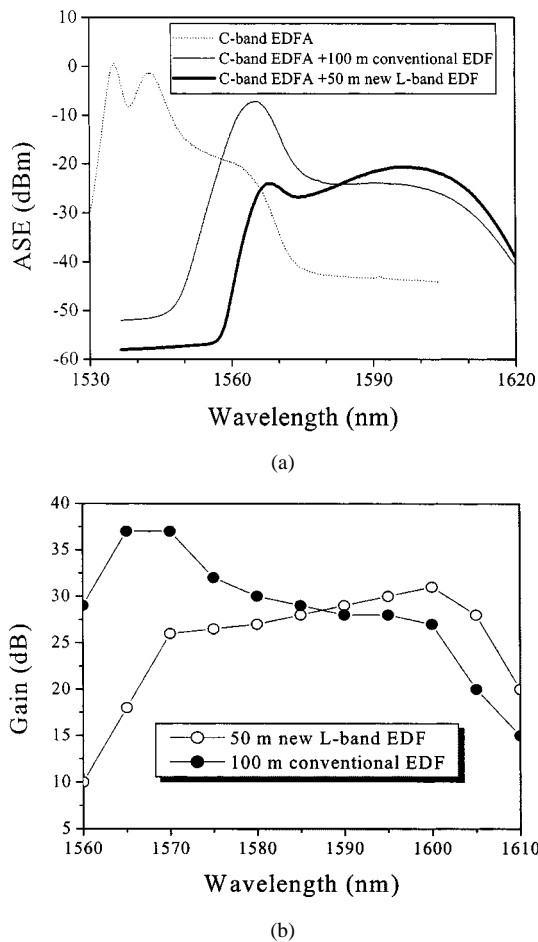


Fig.1. Optical spectral characteristics. (a) ASE shift from C-band to L-band induced in EDF. (b) Small-signal gain.

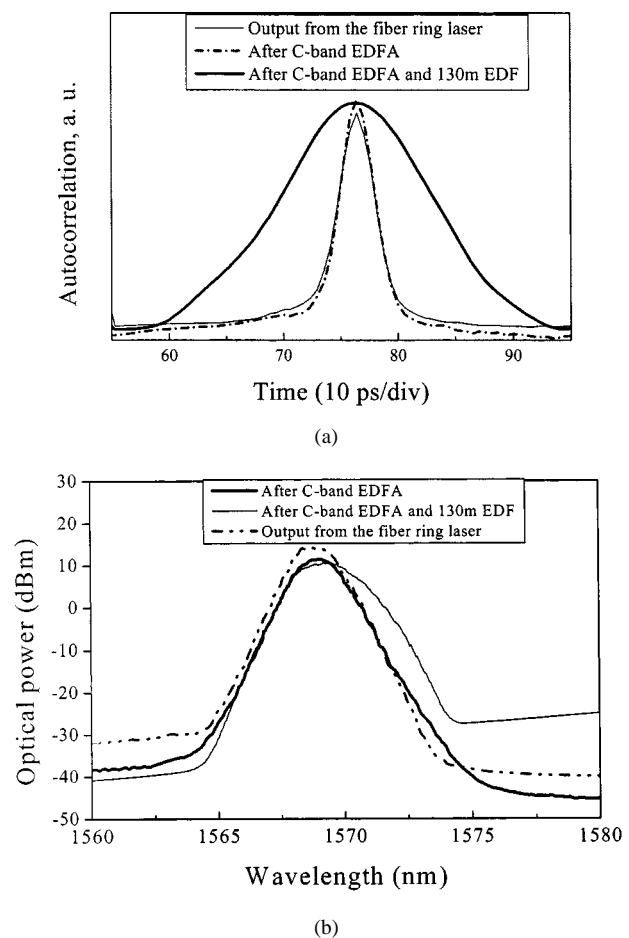


Fig. 2. Optical pulse characteristics. (a) Autocorrelator traces. (b) Optical spectra.

from a commercial erbium-fiber ring laser with 1568 nm as the longest possible wavelength. The short pulse was amplified by 130-m conventional EDF that was pumped by a conventional C-band EDFA, giving up to 14 dBm of output power. Fig. 2 shows the experimental results. Because the EDF length in the C-band EDFA is only a few meters, the SPM effect in the C-band EDFA is very small and the pulsewidth and optical spectrum of the short pulses are not changed after the C-band EDFA. However, after 130-m EDF, the pulsewidth is broadened to 9.9-ps FWHM and the optical spectrum is also broadened. When 2.3-ps short pulse propagates over 130-m EDF, the pulse is broadened to 2.4 ps only if the dispersion effect is considered; this clearly shows that the dispersion effect in the EDF plays a small role, however, the pulse will be broadened when combining SPM and dispersion, as shown in our experimental result.

C. Comparing Pulsewidths for L-Band EDFAs Consisting of Different Kinds of EDFs

In this section, we will experimentally investigate the pulsewidth when the short pulse is amplified by L-band EDFAs consisting of different kinds of EDFs. The experimental setup is shown in Fig.3. We use wavelength conversion based on a nonlinear optical loop mirror (NOLM) to obtain pulses with different wavelengths at L-band [7]. The control laser is a

10-GHz 1560.6-nm gain-switched DFB-LD that generates 9.3-ps FWHM pulses after compression in a dispersion compensating fiber (DCF). In addition, we use a comb-dispersion profiled fiber (CDPF) to further compress the width of the control pulses to 2.4 ps. The control pulses are coupled into the NOLM using a wavelength independent 3-dB optical coupler. The continuous wave (CW) lightwave is generated from an ECL. The CW lightwave having a wavelength in the 1530–1568-nm range is amplified to an average power of 14 dBm by a conventional C-band EDFA. A CW lightwave between 1570–1580 nm was also generated by the ECL but was amplified by 130-m EDF that was pumped by a conventional C-band EDFA, giving up to 14 dBm of output power. A 1.5-nm bandpass TOF at the output of the NOLM is used to suppress the control pulses. The average power of the converted pulses after the TOF is –15 dBm. The length of the HNL-DSF in the NOLM used for wavelength conversion is 0.5 km. The zero dispersion wavelength, dispersion slope, and the nonlinear coefficient of this HNL-DSF are 1552 nm, 0.022 ps/nm²/km, and 10.9 W⁻¹km⁻¹, respectively. The L-band converted pulses are amplified by 100- or 130-m conventional EDF or by 50-m new L-band EDF pumped by a conventional C-band EDFA.

The measured FWHM-pulsewidth of the converted pulses as a function of wavelength of the CW lightwave is shown in Fig. 4. We assume that the waveforms of the converted pulses

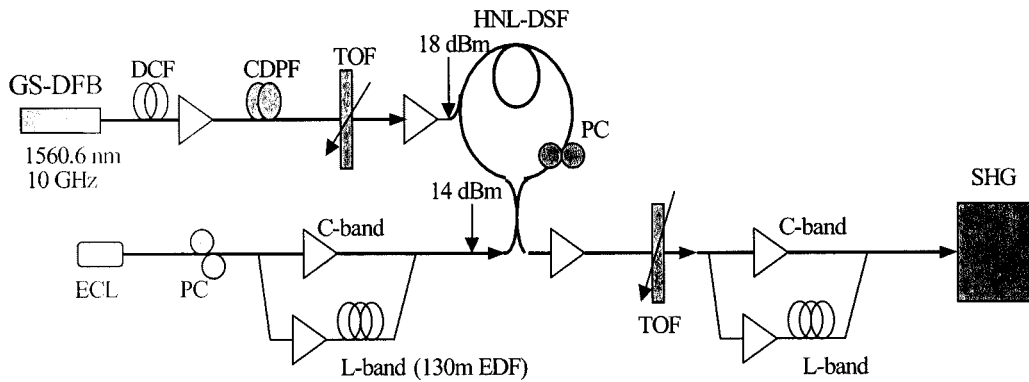


Fig. 3. Experimental setup for generation of short pulses at different wavelengths. GS-DFB-LD: Gain-switched distributed feedback laser diode. DCF: Dispersion compensating fiber. CDPF: Comb-dispersion profiled fiber. TOF: Tunable optical filter. HNL-DSF: High-nonlinearity dispersion shifted fiber. PC: Polarization controller. SHG: Second harmonic generation.

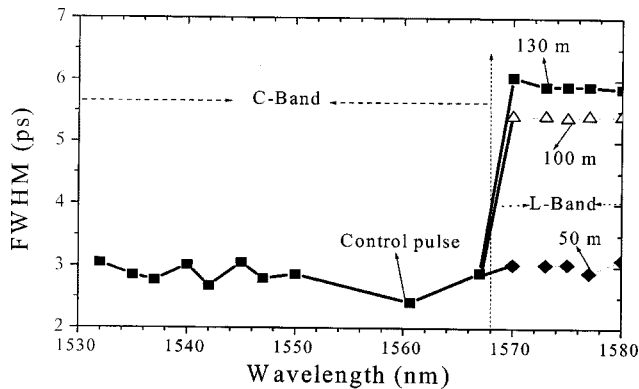


Fig. 4. FWHM pulsewidth of converted pulses as a function of CW wavelength, and SHG traces of converted pulses at 1575 nm by L-band EDFA consisting of different kinds of EDFs.

have Gaussian shape, so that the FWHM pulsewidth is equal to the second-harmonic generation (SHG) auto-correlation trace pulsewidth divided by $\sqrt{2}$. Observing Fig. 4, we can see that the pulsewidth is approximately 3 ps when the CW lightwave wavelength is varied from 1532 to 1567 nm. The slightly broadened pulsewidth is caused by the limited bandwidth of the optical filter. Our experiment shows that when a short pulse with a pulsewidth of 2.4 ps passes through an optical filter with a bandwidth of 1.5 nm, the pulsewidth will be broadened to approximately 3 ps. However, in the L-band, the pulsewidth is about 6 ps and almost constant, when the 130-m conventional EDF is used. The pulsewidth after the L-band EDFA at 1575 nm is 5.9 ps, while the pulsewidth after the C-band EDFA at 1534 nm is only 2.7 ps. Although the change in walkoff time from 1570 to 1580 nm is large, the width of the converted pulses is almost constant; this shows that the walkoff in this wavelength range only has a small effect on the width of the converted pulses. If there were no SPM in the L-band EDFA, and because the walkoff effect in the NOLM can almost be ignored, the pulsewidth after wavelength conversion at 1573 nm should also be 2.7 ps, but it is actually 5.9 ps. This shows that the pulsewidth after the L-band EDFA based on a conventional EDF is broadened. When the conventional EDF with a length of 100 m is used, the pulsewidth is about 5.4 ps and almost constant. However, when the new

L-band EDF with a length of 50 m is used, the pulsewidth is 3 ps. This demonstrates that SPM has a very small effect when the new L-band EDF is used.

III. CONCLUSION

We have observed that 2.3-ps optical pulses are broadened to several times that of the input pulsewidth after amplification in an L-band EDFA consisting of a conventional EDF; this observation implies that a short pulse with pulsewidths smaller than 3 ps should not be amplified by such an L-band EDFA. A new L-band EDF with a large Er^{3+} concentration and a large effective area has been designed and used in a new L-band EDFA. Our experimental results show that a short pulse amplified by the new L-band EDFA will not be broadened, which means that the broadening effect that was caused by SPM has been eliminated.

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